LEVEL II

Cold Air Inhalation, Esophageal Temperature and Lung Function In Exercising Humans

Running Title: Cold Air Inhalation

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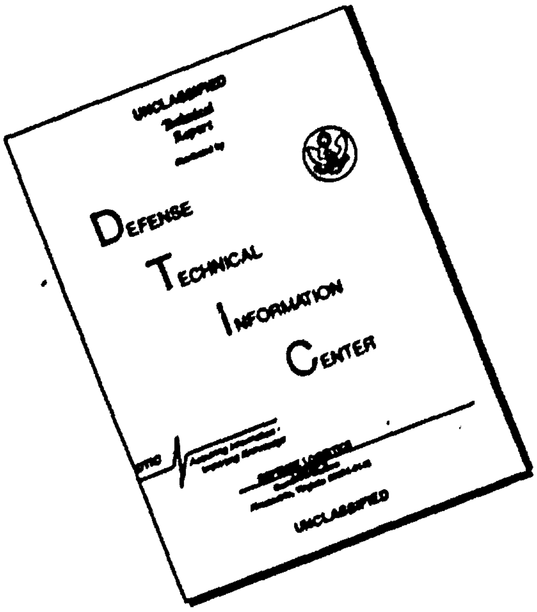

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Eight normal individuals performed 10 min of bicycle exercise at 80% of their predicted maximum workload while breathing air at 22°C, saturated with water vapor and air at -40°C, dry. Rectal temperature (T_{re}) and temperature at various locations along the length of the esophagus were measured during the exercise period. Pulmonary mechanics were measured before and 5 to 10 min after exercise. Temperature in the lower third of the esophagus was in close agreement with T_{re} and was unaffected by level of respiratory heat exchange. Upper esophageal

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temperature decreased substantially during exercise, the magnitude of the decrease being dependent upon proximity to intrathoracic airways and the level of respiratory heat exchange. Subjects bronchodilated in response to exercise breathing warm air but this response was abolished by exercise breathing -40°C air. We conclude that at sufficiently high levels of respiratory heat exchange, normal individuals exhibit mild bronchoconstriction qualitatively similar to the severe bronchospasm induced in asthmatics by modest increases in respiratory heat exchange.

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Abstract

Eight normal individuals performed 10 min of bicycle exercise at 80% of their predicted maximum workload while breathing air at 22°C, saturated with water vapor and air at -40°C, dry. Rectal temperature (T_{re}) and temperature at various locations along the length of the esophagus were measured during the exercise period. Pulmonary mechanics were measured before and 5 to 10 min after exercise. Temperature in the lower third of the esophagus was in close agreement with T_{re} and was unaffected by level of respiratory heat exchange. Upper esophageal temperature decreased substantially during exercise, the magnitude of the decrease being dependent upon proximity to intrathoracic airways and the level of respiratory heat exchange. Subjects bronchodilated in response to exercise breathing warm air but this response was abolished by exercise breathing -40°C air. We conclude that at sufficiently high levels of respiratory heat exchange, normal individuals exhibit mild bronchoconstriction qualitatively similar to the severe bronchospasm induced in asthmatics by modest increases in respiratory heat exchange.

respiratory heat exchange, rectal temperature, asthma

Introduction

A recent report from this laboratory has demonstrated that upper esophageal temperature, and by implication, upper airway temperature, falls considerably during exercise while breathing air at approximately $-16^{o}C$ (4). Decreases in esophageal temperature were directly related to the degree of post-exertional airway obstruction in subjects with exercise-induced asthma. In contrast, normal subjects developed no post-exertional obstruction despite similar degrees of airway cooling. While this data indicate that asthmatics are responsive to the effects of incomplete conditioning of inspired air, it does not indicate at what point (if at all) increased respiratory heat exchange will impair lung function in normal individuals. The purpose of this experiment was to extend the measurement of post-exertional lung function in normals to an inspired air temperature of approximately $-40^{o}C$, a temperature likely to be encountered only by individuals living in arctic regions. Another objective was to obtain a more detailed map of temperature along the length of the esophagus during high levels of respiratory heat exchange.

Methods

Eight individuals with no history of cardiopulmonary disease participated in this study. Informed consent was obtained from each subject. Anthropometric data is contained in table 1. Several days prior to testing, the maximum oxygen consumption ($\dot{V}_{O_{2max}}$) of each subject was predicted from a sub-maximal exercise period on a bicycle ergometer (1). The anatomic relationship of each subject's esophagus to other mediastinal structures was defined by having them swallow a balloon-tipped catheter into the stomach via the nose. Pressure in the balloon relative to atmospheric pressure was measured by a differential transducer and recorded as the catheter was slowly withdrawn from the stomach and advanced up the esophagus. During this procedure the linear distance from the nares to the tip of balloon was noted so as to locate the gastroesophageal junction, the point of maximum cardiac artifact and the lowest point in the esophagus at which movement of the trachea produced a pressure artifact. These distances were recorded and used to select the initial placement site of the temperature probes.

On the day of testing each subject had 2 vinyl-sheathed copper-constantan thermocouples (Bailey Instrument Co.) inserted through the nares into the esophagus. The probes were positioned at points approximately 80% and 60% of the distance from the nares to the gastroesophageal junction (GEJ). To insure that the probes maintained a constant spatial relationship, they were taped together before insertion, and subsequently secured at the nares to avoid movement during exercise. Rectal temperature (T_{re}) was measured by a third thermocouple inserted approximately 10 cm into the rectum. Each of the three thermocouples of a set were matched for response time and temperature reading in various thermal baths between 20 and 50°C. The 90% response time of the thermocouples to a step change in temperature in a still water bath was approximately 40 seconds. Temperatures measured by the three probes were printed every 7 sec along with other temperature information on a data terminal connected to a digital thermocouple scanner with 0.1°C resolution (Leeds and Northrup).

The temperature and water content of the inspired air was controlled by having the subjects breathe through a heat exchanger and bubble humidifier as described previously (9). To achieve inspired air temperatures as low as -60°C, the circulating, refrigerated alcohol bath was replaced by a high capacity cooling unit (FTS Systems model FC-100-84-P2) with the evaporator coil placed inside the inspired air heat exchanger. Temperature of the inspired air was measured by a thermocouple located within the airstream in the exchanger, 10 cm upstream from the mouth. Expired gas was directed away from the exchanger through a one-way valve into a Tissot Spirometer so that minute ventilation ($\dot{V}_E$) could be recorded. Heart rate was monitored continuously.

Airway resistance and total lung capacity with its subdivisions were measured in a variable pressure plethysmograph that was serially interfaced to an analog recorder (Electronics for Medicine) and a minicomputer (Lab 8E, Digital Equipment Corp). Resistance was converted to its reciprocal, conductance, and expressed as a conductance volume ratio termed specific conductance (SG_{aw}) (2). Four to five measurements of each variable were obtained, and the mean was computed. These data were considered acceptable if their coefficients of variation were 5% or less. Maximum forced exhalations were then performed in triplicate using a waterless spirometer (Electro Med. Model 780, Searle Cardiopulmonary). One second forced expiratory volumes (FEV_1) and maximum mid-expiratory flow rates were computed by standard techniques. The best effort, as defined by the curve with the largest forced vital capacity and FEV_1, was used for analysis.

Esophageal and rectal temperatures were measured before and during 10 min of bicycle exercise at approximately 80% of the workload predicted to elicit $\dot{V}_{O_{2\,max}}$ from each individual. Exercise was performed at room temperature with subjects wearing gym shorts and T-shirts. Exercise was performed breathing air at approximately 22°C and saturated with water vapor and a second time breathing air at approximately -40°C and dry. Half the subjects exercised breathing warm air during their first exercise period; the other half breathing -40°C air first. The two exercise periods were separated by at least 3 hours of rest. During the first 7 min of exercise, esophageal temperatures were recorded from the initial thermocouple locations of 60 and 80% of the distance from nares to GEJ. During the final 3 min of the exercise period the two esophageal probes were advanced as a pair 4 times in 2.5 cm increments, with approximately 40 sec between moves. Thus, a temperature map covering the segment between 40% and 80% of the distance from nares to GEJ was obtained. For the group, this represented a 20.6 ± 0.4 cm (mean ± SE) segment of the esophagus between 23.1 ± 0.8 cm and 43.7 ± 1.1 cm from the nares. Pulmonary mechanics were measured before and 5 to 10 min after each exercise period.

The data were analyzed by a one or two factor analysis of variance as appropriate for either unpaired or paired comparisons.

Results

The predicted maximum oxygen consumption for the 8 subjects averaged 3.7 ± 0.2 (SE) L min^{-1}. The distance from the nares to the gastroesophageal junction averaged 55 ± 1 cm (table 1). With each subject exercising at 80% of the workload predicted to elicit $\dot{V}_{O_{2max}}$, minute ventilation breathing warm and cold air averaged 77.7 ± 6.4 and 72.3 ± 5.8 L min^{-1}, respectively (table 2). The corresponding exercise heart rates for warm and cold air breathing were 170 ± 4 and 171 ± 3 beats min^{-1} (table 2).

The inspired air temperatures for each subject for warm and cold air breathing are shown in table 2. While exercising and breathing warm saturated air, the inspired air temperatures averaged 21.5°C. The inspired air temperatures during cold air breathing averaged -41.5°C.

Figures 1 and 2 depict the time course of rectal and esophageal temperatures during the first 7 min of exercise while breathing warm and cold air. In both instances rectal temperature was higher than either upper (T_{es_1}) or lower (T_{es_2}) esophageal temperature at the start of the exercise period. During the 7 min of exercise, T_{re} changed little with the values for minute 7 of exercise being 0.1 to 0.2°C higher than those at the start. Temperature measured at 80% of the nares to GEJ distance down the esophagus (T_{es_2}) rose steadily throughout the exercise period for both warm and cold air breathing and was indistinguishable from rectal temperature from the fifth minute on. In contrast, temperature measured at 60% of the nares to GEJ distance down the esophagus was less than T_{re} and T_{es_2} at all times for both warm and cold air breathing. For subjects breathing warm saturated air, T_{es_1} decreased approximately 0.6°C within 3 min of the start of exercise and remained at this level until minute 6 of exercise when a slight warming trend was observed. For subjects breathing cold, dry air, T_{es_1} decreased more rapidly than during warm air breathing and reached a level 2.6°C less than the initial temperature by minute 6.

Figure 3 depicts the esophageal temperature data obtained during the final 2 to 3 min of exercise while the two temperature probes were advanced up the esophagus. Relative to rectal temperature, esophageal temperature decreased as the point of measurement moved toward the nasopharynx for both warm and cold air breathing. There was relatively little effect of inspired air temperature on T_{es} measured anywhere between 80 and 65% of the nares to GEJ distance down the esophagus. However, from 65 to 40% of the nares to GEJ distance, inspired air temperature had a substantial effect on the magnitude of the difference between T_{re} and T_{es}. For example, at a point 50% of the nares to GEJ distance down the esophagus, the rectal-esophageal temperature difference averaged $2.2 \pm 0.1^{\circ}C$ during warm air breathing but averaged $5.5 \pm 0.5^{\circ}C$ during cold air breathing.

The effects of exercise while breathing warm or cold air on pulmonary mechanics are shown in table 3. Relative to pre-exercise values, breathing warm air during exercise resulted in small but statistically significant increases in residual volume (1.52 ± 0.11 vs 1.66 ± 0.14 L) and FEV_1 (4.40 ± 0.25 vs $4.53 \pm$ L sec^{-1}) but no change in specific conductance (0.20 ± 0.02 vs 0.19 ± 0.02 L sec^{-1} cm H_2O^{-1} L^{-1}). In contrast, exercise breathing cold air did not elicit a significant change in residual volume or FEV_1 but did result in a significant decrease in specific conductance (0.22 ± 0.02 vs 0.20 ± 0.03 L sec^{-1} cm H_2O^{-1} L^{-1}).

Discussion

The temperature and water content of the inspired air selected for the cold and warm air breathing phases of this study produced two extreme conditions of respiratory heat exchange. The amount of heat transferred from the mucosal surfaces of the nasopharynx and airways in the process of warming and humidifying inspired air may be calculated for each experimental situation. Using methods described previously (6) and assuming ventilation of 75 L/min, we estimate that 1070 kcal are required to condition air initially at 22°C and saturated. To condition dry air at -40°C, approximately 1915 kcal are needed. These are estimates of heat exchange during inspiration only. Since mucosal cooling during inspiration results in partial heat and water recovery during expiration, net respiratory heat exchange is considerably less than indicated above. With subjects exercising at 80% of their predicted maximum aerobic work capacity, there was no discernable effect of level of respiratory heat exchange upon steady state heart rate or ventilation (table 2). These observations reflect the minor role of the magnitude of this aspect of whole body heat exchange in determining the cardio-respiratory response to moderate exercise in a non-stressful thermal environment.

Esophageal temperature at any point is determined by the temperature of the arterial blood supply, local metabolic rate, mucosal blood flow and heat exchange with adjacent structures. Temperature measured in the lower third of the esophagus has long been used as an estimate of core temperature and has an advantage over rectal temperature in that T_{es} responds faster than T_{re} when body temperature is altered. In both phases of this study, T_{es_2} was approximately 0.6°C less than T_{re} at rest but became statistically indistinguishable from T_{re} after 5 min of exercise. It is assumed that the proximity of the T_{es_2} measurement point to the heart and large blood vessels is the reason for this quick response to the increased heat production of exercise.

For both warm and cold air breathing, the temperature measured in the upper esophagus (T_{es_1}) was within 1.5°C of rectal temperature at rest but decreased markedly during the exercise period. Furthermore, the magnitude of the fall in T_{es_1} was clearly influenced by the level of respiratory heat exchange. The anatomical location of the T_{es_1} probe was the lowest point at which external manipulation of the trachea produced a pressure artifact on the record of esophageal balloon pressure, a point at which the cardiac pressure artifact was substantially less than at lower locations in the esophagus. In the absence of radiographic evidence we feel it reasonable to assume that the T_{es_1} probe was in close proximity to the carina. Therefore, we conclude that T_{es_1} represents the upper limit for the estimate of airstream temperature in that region of the thorax for the levels of respiratory heat exchange employed. The data in figure 3 summarizes the relationship between esophageal temperature, point of measurement and respiratory heat exchange. T_{es} measured in the lower third of the esophagus is a reasonable estimate of core temperature regardless of level of respiratory heat exchange. However, as the point of measurement moves away from the heart and toward the large airways, temperatures substantially less than rectal temperature may be recorded. The magnitude of the discrepancy is greatly influenced by the level of respiratory heat exchange.

This finding of intrathoracic cooling had been reported earlier by Cranston (3); however, the magnitude and implications of the effect of respiratory heat exchange on esophageal temperature have not been fully appreciated. Recent clinical studies (4,5,6) have renewed interest in esophageal temperature measurement in the region where the trachea and esophagus are in apposition. These experiments have shown that there is a strong correlation between post-exertional airway obstruction in asthmatics and temperature drop in intrathoracic airways as assessed by esophageal temperature. Airway obstruction did not develop in normal individuals with similar degrees of airway cooling (4). The changes in pulmonary mechanics reported for normals breathing 22°C and -40°C air in this study suggest that the post-exertional bronchodilation observed in normals under conditions of relatively low respiratory heat exchange is attenuated if the level of respiratory heat exchange is sufficiently high. Bronchodilation after exercise in normals has been reported by others (7, 8). Although the mechanism involved is not known, the observation that this response may be abolished following exercise breathing air at -40°C suggests that the mechanism producing substantial airway obstruction in asthmatics following exercise is also active in normals but to a much lesser extent.

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The views, opinions, and findings contained in this report are those of the authors and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other official documentation.

Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRDC Regulation 70-25 on Use of Volunteers in Research.

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Table 1. Subject age, height, weight, predicted maximum oxygen consumption ($\dot{V}_{O_{2max}}$), and distance from nares to the gastroesophageal junction (Nares to GEJ).

Subject	Age (yr)	Height (cm)	Weight (kg)	$\dot{V}_{O_{2max}}$ ($L\ min^{-1}$)	Nares to GEJ (cm)
1	31	173	81.8	3.4	56
2	24	168	75.9	3.3	56
3	29	160	69.1	3.6	48
4	24	190	108.5	4.8	55
5	24	175	84.0	4.1	55
6	24	170	61.2	3.0	55
7	31	178	82.3	3.7	57
8	26	184	69.8		60
mean	27	175	79.1	3.7	55
SE	1	3	5.0	0.2	1

Table 2. Inspired air temperature (T_i), minute ventilation ($\dot{V}_E$) and heart rate (HR) for subjects breathing warm and cold air.

	Warm Air (saturated)			Cold Air (dry)		
Subject	T_i (°C)	$\dot{V}_E$ (L min^{-1} BTPS)	HR (min^{-1})	T_i (°C)	$\dot{V}_E$ (L min^{-1} BTPS)	HR (min^{-1})
1	21.5±0.2	71.8	176	-41.7±0.4	73.2	172
2	20.5±0.1	62.7	165	-40.3±0.4	60.7	176
3	21.0±0.1	69.0	175	-41.3±0.4	65.3	170
4	22.1±0.1	92.0	165	-41.7±1.0	----	160
5	21.4±0.1	----	175	-43.3±1.1	70.5	180
6	21.2±0.1	64.0	168	-42.7±0.3	60.1	162
7	22.3±0.3	75.2	150	-40.6±0.3	71.3	160
8	22.5±0.1	109.0	184	-40.6±0.7	105.0	184
mean	-------	77.7	170	---------	72.3	171
SE		6.4	4		5.8	3

Values for T_i are the mean ± SE of 15 observations taken at 0.5 min intervals during the exercise period.

V_E and HR measured during the last minute of exercise.

Table 3. Conductance (SG_{aw}), residual volume (RV), and one-second forced expiratory volume (FEV_1) before (B) and after (A) exercise while breathing warm or cold air.

	Warm Air						Cold Air					
	SG_{aw}		RV		FEV_1		SG_{aw}		RV		FEV_1	
Subject	B	A	B	A	B	A	B	A	B	A	B	A
1	0.19	0.16	2.12	2.25	3.72	3.85	0.18	0.16	2.07	2.08	3.62	3.64
2	0.32	0.28	1.23	1.28	4.68	4.70	0.37	0.36	1.38	1.37	4.66	4.69
3	0.13	0.14	1.37	1.35	2.96	3.09	0.22	0.13	1.24	1.37	3.10	2.89
4	0.24	0.23	1.41	1.48	4.87	4.95	0.21	0.18	1.50	1.70	4.90	4.84
5	0.22	0.19	1.27	1.45	4.92	5.23	0.24	0.24	1.06	1.05	5.10	5.26
6	0.13	0.13	1.76	2.09	4.53	4.77	0.14	0.13	1.79	2.17	4.54	4.55
7	0.19	0.24	1.62	2.01	4.97	5.10	0.21	0.19	1.82	2.03	4.89	4.88
8	0.17	0.18	1.34	1.35	4.52	4.52	0.19	0.18	1.47	1.43	4.41	4.46
mean	0.20	0.19	1.52	1.66*	4.40	4.53*	0.22	0.20*	1.54	1.65	4.40	4.40
SE	0.02	0.02	0.11	0.14	0.25	0.25	0.02	0.03	0.12	0.14	0.25	0.27

Units are as follows: SG_{aw}, L sec^{-1} cm H_2O $^{-1}$ L $^{-1}$; RV, L; FEV_1, L. All volumes are BTPS.

* Significantly different from pre-exercise value $p<0.05$.

Figure Legends

Figure 1. Rectal temperature (T_{re}), upper (T_{es_1}) and lower (T_{es_2}) esophageal temperature at rest (-1 to 0 min) and during the subsequent 7 min of exercise. Values are the mean ± SE, n=8. Inspired air temperature (T_i) = 22°C, saturated with water vapor.

Figure 2. Rectal temperature (T_{re}), upper (T_{es_1}) and lower (T_{es_2}) esophageal temperature at rest (-1 to 0 min) and during the subsequent 7 min of exercise. Values are the mean ± SE, n=8. Inspired air temperature (T_i) = -40°C, dry.

Figure 3. Mean difference (± SE) between rectal temperature (T_{re}) and esophageal temperature (T_{es}) as a function of the distance from the nares to the gastroesophageal junction (GEJ) (mean ± SE), for both warm (T_i = 22°C) and cold (T_i = -40°C) air breathing during exercise, n=8.

Fig 1

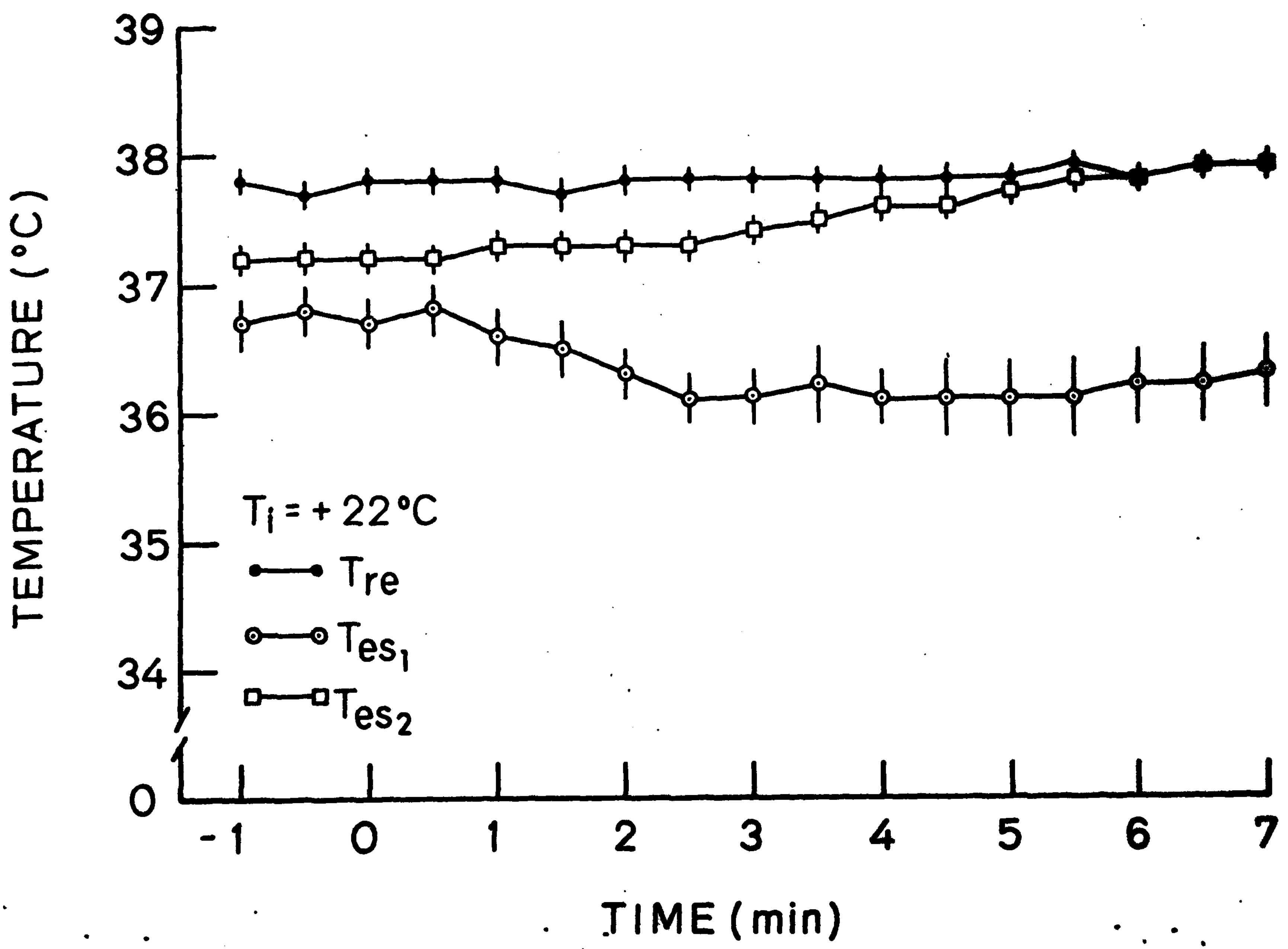

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Fig 2

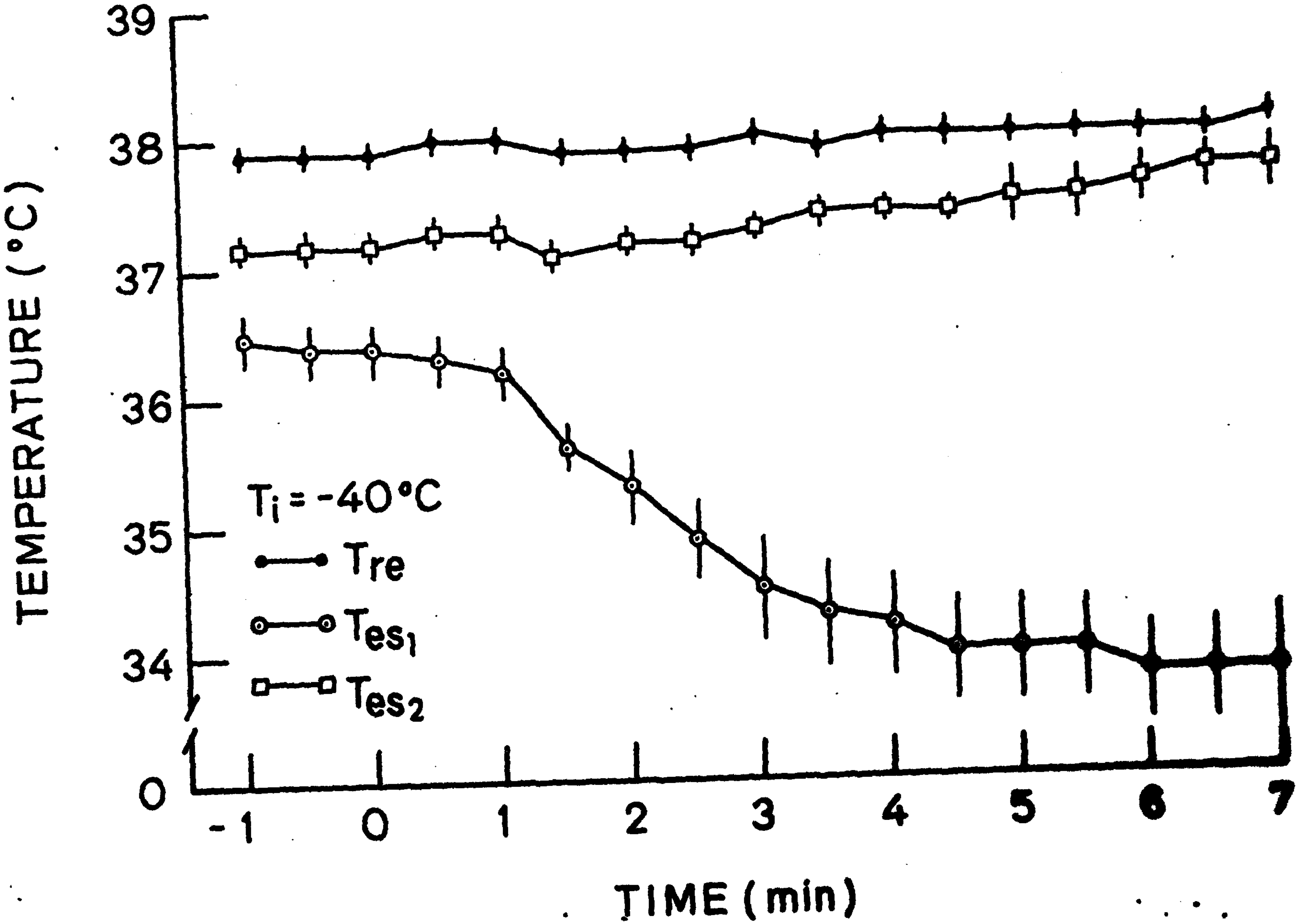

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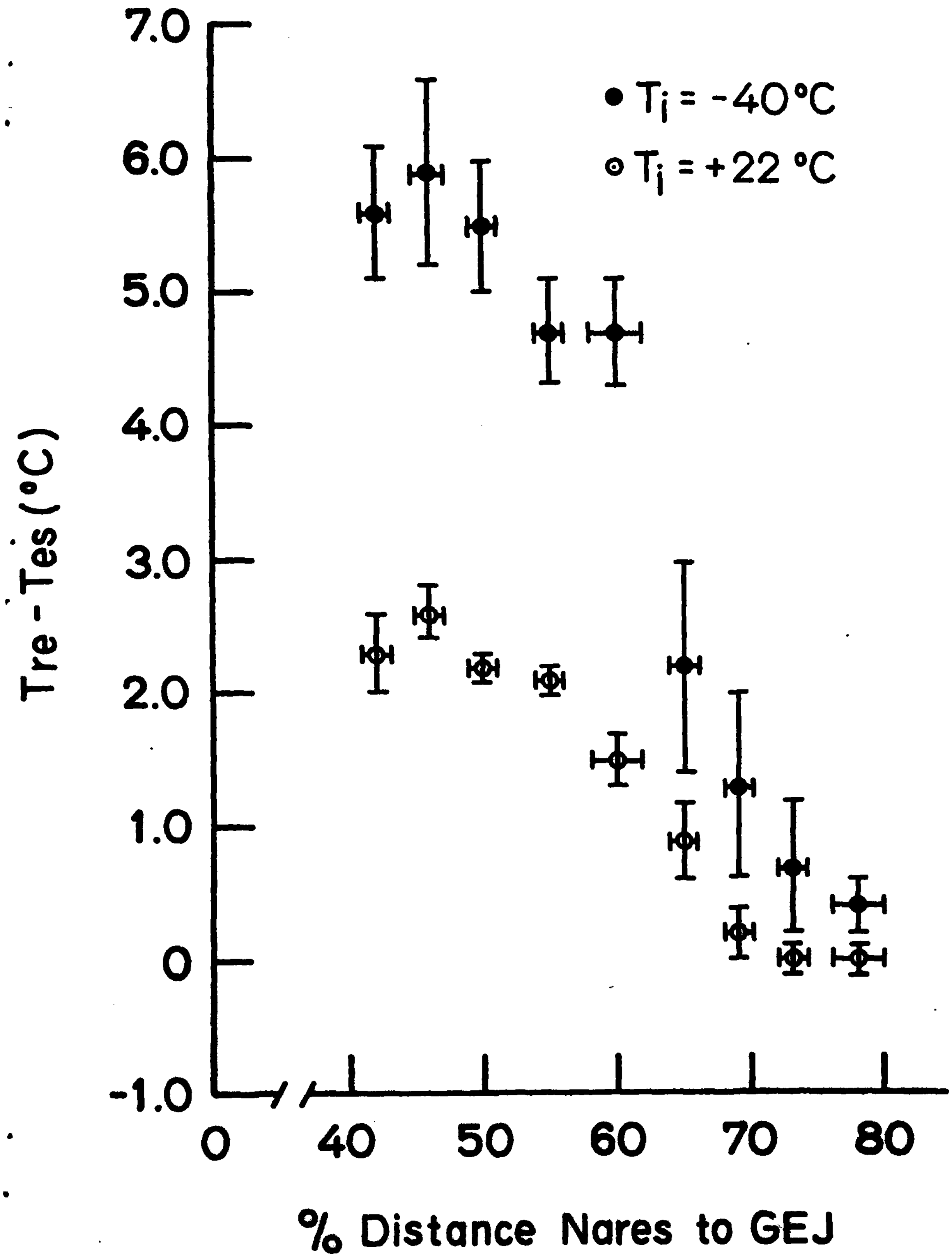
Fig 3



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